A structured response to the Scottish landslide events of August 2004

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Abstract: In August 2004 a series of landslides in the form of debris flows occurred in Scotland. Some of these affected the A83, A9 and A85, which form important parts of the trunk road network linking both cities and smaller, remote communities.

While debris flows occur with some frequency in Scotland, they only rarely affect the trunk road network or for that matter the main local road network. However, when they do impact on the road network the degree of damage, in terms of the infrastructure and the loss of utility to road users, can have a major detrimental effect on both economic and social aspects of the use of the asset. Additionally, there is a high potential for such events to cause serious injury and even loss of life although, fortuitously, such consequences have been limited to date.

The events of August 2004 followed a sustained period of heavy rainfall and, in addition, intense localised storms contributed to the triggering of at least some of the resulting debris flows. Rainfall of up to 300% of the monthly average fell in certain parts of Scotland during August 2004.

The impacts of such events are particularly serious during the summer months due to the major contribution that tourism makes to Scotland's economy. Nevertheless, the impacts of debris flow events during the winter months should not be underestimated.

This paper briefly describes both the events of August 2004, including their impacts, and some earlier events. The main focus of the paper is the structured approach being taken to the hazard assessment, ranking and management in respect of future events.

Résumé: En Aout 2004, une série de glissements de terrain sous forme d'écoulement de débris se sont produits en Ecosse. Certains de ces glissements ont affecté la A83, la A9 et la A85, qui constituent des éléments importants du réseau des grands axes routiers reliant les grandes villes aux communautés plus petites et plus éloignées.

Bien que les écoulements de débris soient assez fréquents en Ecosse, ils affectent rarement le réseau des grand axes routiers ni d'ailleurs le réseau des principales routes locales. Toutefois, lorsqu'ils affectent le réseau routier, les dommages causés à l'infrastructure et la perte de l'usage de la voie routière pour les usagers peuvent avoir des répercutions négatives importantes sur les aspects sociaux et économiques associés à l'utilisation de ce service. Il existe par ailleurs la très réelle possibilité que ce genre d'événements cause des blessures sérieuses ou même mortelles, bien que, par chance, ces conséquences ont été jusqu'ici limitées.

Les événements d'aout 2004 suivirent une période de fortes précipitations tandis que par ailleurs, de très forts orages localisés contribuèrent à déclencher au moins certains des écoulements de débris qui s'ensuivirent. Des précipitations de plus de 300% de la moyenne mensuelle affectèrent certaines parties de l'Ecosse pendant le mois d'aout.

L'impact de ce genre d'événements est particulièrement sérieux durant les mois d'été étant donné la contribution majeure à l'économie écossaise que représente le tourisme. Il ne faut cependant pas sous-estimer l'impact des écoulements de débris durant les mois d'hiver.

Cet article décrit brièvement les événements du mois d'aout 2004 ainsi que leur impact, et certains événements antérieurs. Le principal centre d'intérêt de cet article est l'approche structurée adoptée pour permettre d'évaluer le danger, l'ordre de priorité adopté et la gestion des événements futurs.

Keywords: geological hazards, highways, infrastructure, landslides, mass movement, risk assessment.

INTRODUCTION

In August 2004 Scotland experienced rainfall substantially in excess of the norm. Some areas of Scotland received more than 300% of the 30-year average August rainfall. In the Perth and Kinross area figures of the order of between 250% and 300% were typical. While the percentage rainfall during August reduced to the west, parts of Stirling and Argyll & Bute still received between 200% and 250% of the monthly average (Source: www.metoffice.com).

The rainfall was both intense and long lasting and a large number of landslides, in the form of debris flows, were experienced in the hills of Scotland. A small number of these intersected with the trunk road network, notably the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August).

While there were no major injuries to those affected, some 57 people were taken to safety by helicopter after being trapped between the two debris flows on the A85 in Glen Ogle (Figure 1). The A85, carrying up to 5,600 vehicles per day (all vehicles two-way, 24 hour AADT), was closed for four days. The A83, which carries around 5,000 vehicles per day, was closed for slightly in excess of a day and the A9 (Figure 2), carrying 13,500 vehicles per day, was closed for two days prior to reopening, initially with single lane working under convoy.

The traffic flow figures are for the most highly trafficked month of the year for each of the roads, either July or August. Minimum flows occur in either January or February and are roughly half those of the maxima. The figures reflect the importance of tourism and related seasonal industries to Scotland's economy.

This paper briefly describes the events of August 2004 and sets these within both the historic and pre-historic context. Also described is the structured response taken by the Scottish Executive to these events. This response is intended to allow the systematic and effective assessment, ranking, management and mitigation of the potential hazards from such events on the Scottish Road Network in the future.

Figure 1. Road users are airlifted to safety in Glen Ogle (© Perthshire Picture Agency: www.ppapix.co.uk).

Figure 2. The southerly debris flow at the A9 north of Dunkeld. The flow has formed its own channel by erosion. (Courtesy of Alan MacKenzie, BEAR.)

DEBRIS FLOW EVENTS

The debris flow events of August 2004 have created a high profile for the effects landsliding activity in the media. It is, however, important to maintain clear sight of the fact that such events are not a recent phenomenon and have occurred in Scotland and elsewhere, at least periodically, during postglacial times.

August 2004 Events

The August 2004 debris flow events commenced on the 8th when the A83 was blocked at two locations in Glen Kinglas, 0.5km and 2.5km from the junction with the A815, and at a point approximately 1km north of Cairndow. The flow at Cairndow had a substantial effect on a residential property immediately upslope from the road (Figure 3). Numerous smaller debris flows were also observed on the hill slopes either side of Glen Kinglas.

Following prolonged rainfall and an intense storm the hillside was in a wet condition and it would appear that the debris flows were triggered by shallow slides of relatively small amounts of material into stream beds, so providing the impetus for further erosion. Several hundred tonnes of material are estimated to have blocked the road at the two locations in Glen Kinglas with possibly two to three times this amount at the Cairndow debris flow. The debris blocking the road comprised very silty sands and gravels with frequent cobbles and boulders, the largest of which was up to nine tonnes. There were smaller boulders remaining within the water courses, although none were considered to be a further threat to the road.

Figure 3. A83 debris flow to the west of Cairndow showing the effects on a roadside cottage and the trunk road immediately downslope from the cottage.

On 11 August just to the north of the Jubilee Bridge near Dunkeld the A9 was blocked by the material from three debris flows. At this point the old A9, which is now largely used for access to a small number of properties, runs upslope and parallel to the trunk road. The slope immediately above the trunk road was cut to a gradient around 1 in 2 at the time of the construction of the road. The slope above then slackens, steepening only for the bench on which rests the old A9.

Following three days of heavy rain, large quantities of water, in excess of what the drainage system could contain and/or disperse, flowed onto the old A9. The water flowed along the old A9 before being channelled onto the slope below in a small number of locations. This had the effect of retarding and concentrating the water into relatively small areas of the slope. At two of these locations instability was caused immediately below the old A9, leading to the formation of gulley features in the cut slope and the deposition of large volumes of debris on the A9 trunk road below. At a third location instability due to the water flow immediately beneath the old A9 was not evident, but a gulley was nonetheless formed in the cut slope (Figure 2). The lack of gulley features in the upper, shallower slope is most likely due to the presence of a stiffer material close to the surface, which was removed during the formation of the cutting and/or the presence of boulders at this level of the strata.

The A9 incidents are by no means the first in which either forest roads or minor roads have acted to retard and concentrate the downslope flow of water and thus aid its penetration into the slope below. Such a mechanism has been a factor in a number of previous events such as the washout that blocked the A83 Rest and be Thankful in the vicinity of Roadman’s Cottage, in 1999. However, in the A9 Slochd failure of July 2002 it was the presence of the trunk road that contributed to the failure of the old road (used as a cycle path) and consequently to its own failure by undercutting. The presence of forest tracks was also identified as a factor in the debris flow at Invermoriston (see below).

On 18 August the A85 in Glen Ogle was blocked by two debris flows. The southern, smaller, flow occurred first followed by the larger northern flow (Figure 1). The debris flow events were preceded by a short but exceptionally intense rain storm which centred on the Lochearnhead and Strathyre area of Stirlingshire on 18 August. This took place during an unusually wet summer, as will be surmised from the previous paragraphs, and followed a prolonged period of heavy rain during the proceeding week.

In common with the debris flows at the A83, those in Glen Ogle appear to have been triggered by relatively small amounts of material slipping into existing stream channels, thus providing the impetus for further erosion downslope. In the case of the northerly flow the stream takes a sharp left turn to avoid a rock outcrop and run parallel to the road for around 40m to 50m prior to making a sharp right turn to negotiate a culvert. The culvert was rapidly blocked and the debris over-topped the road causing substantial damage to the parapets of the culvert structure. In its latter phases the debris over-topped the rock outcrop (visible to the left of Figure 1) sweeping a Trunk Road Operating Company vehicle down the slope and into a tree. Fortunately the driver and passengers had left the vehicle to offer advice to road users.

A more detailed description of the events of August 2004 is given by Winter *et al*. 2006.

Historic and Prehistoric Events

It is important to note that debris flows are neither a recent phenomenon nor an uncommon occurrence. The first church in the Falkland Islands, for example, was wrecked in 1886 when a "river of liquid peat … roared down from the hills" (Winchester 1985). Closer to home, a cloud burst in 1744 resulted in the flow and associated erosion of the gulley below the summit of Arthur's Seat known today as the Gutted Haddie (McAdam 1993).

Innes (1983) made a survey of Scotland based upon aerial maps and marked those 10km by 10km grid squares that showed some sign of debris flow activity, clearly indicating that such activity is widespread. It is, however, important to note that Innes map does not indicate debris flow activity in the area around the Rest and be Thankful, for example, and this work should not be viewed as exhaustive (Winter *et al*. 2005a). Further, radiocarbon dating of materials associated with debris flow activity by Innes (1982) indicates that such activity has occurred throughout most of the last 7,000 years, albeit with clustering of the data which may be indicative of periods of higher and lower levels of activity (Ballantyne 2004). However, based upon stratigraphic evidence, Ballantyne (2004) also suggests that such activity was widespread after ice-sheet deglaciation and during and after ice retreat at the end of the Loch Lomond Stade approximately 11,500 years ago. Clearly debris flows are not a recent phenomenon in Scotland.

It is clear that the August 2004 events in Scotland had the potential to cause injury and even death. However, such potential was not on the same scale as the reality that is experienced elsewhere in the world on a regular basis. For example, in September 2004, torrential rain triggered massive floods and landslides in SW China, killing in excess of 170 people and injuring many dozens more (Sources: *The Independent*, 8 September 2004 and *BBC World*, 9 September 2004). The potential for loss of life due to landslides in Scotland seems compared to the estimated 5,000 plus fatalities per annum worldwide (Petley *et al*. 2005).

Recent Debris Flows

In recent years debris flow events appear to have had a more regular effect on the Scottish trunk and local road network, together with the Scottish rail network. At face value this suggests that such events have become more common. Such a conclusion would however be somewhat speculative as comprehensive, detailed records are not generally available for events that do not impact upon man's activities. Notwithstanding this Ballantyne (2004) estimates return periods of between <10 years and several decades for debris flows at susceptible sites in Scotland over the last 50 years. What does appear clear from simple observation is that many debris flows are initiated on the Scottish hills. However, only a relatively small number turn into major events that impact upon road networks or other forms of infrastructure. This implies that in order to manage the impacts of debris flows it is necessary to understand the preparatory factors (that make a slope vulnerable to debris flows), the trigger factors (that lead to initiation of flows) and any propagation and/or magnification factors as discussed in Winter *et al*. (2005a).

In the recent past debris flows have commonly occurred in the month of August. One such example is an event that intersected the A887 at Invermoriston in 1997 (Figure 4). This event was studied in detail and found to have been triggered at a point almost 300m vertically and around 2,000m horizontally from the road, close to the source of the stream which subsequently contained most of the event. A number of contributory factors were established (Nettleton *et al*. 2005), including the following:

- The lack of water storage volume within the catchment, both above and below ground.
- The ploughing of agricultural land increases and accelerates runoff into streams.
- The presence of downslope bedding planes.
- Low permeability bedrock.
- The presence of forestry bridges which temporarily arrested the flow allowing material to accumulate and subsequently remobilise with greater erosive power.
- The presence of a buried cliff providing a large amount of debris at a point close to the road.
- A steep slope close to the road.

Many of the features of the slope at Invermoriston, such as its convex shape (i.e. steepening downslope) are characteristic of glacial valleys which are in turn typical of much of the landscape of Scotland. The event was preceded by rainfall of both long duration and high intensity. As a result of the debris flow the road was closed, damage was sustained to vehicles and a local hotel only narrowly escaped substantial damage.

Debris flow events have also been observed at other times of the year. They have affected both the A890 and the railway at Stromeferry in January 1999, October 2000 and October 2001 (Figure 5). The January 1999 and October 2000 events were characterised by the mobilisation of material from a pre-existent landslide which slipped into a gully thus providing the source material for the debris flow event. The October 2001 event was propagated from a gully that had been infilled with silt, gravel and cobble fractions. In each case disruption to the road and railway was experienced.

The effects of forestry have frequently been identified as, at least, partial causes or propagators of debris flows in areas such as the Pacific NW of the USA (Brunengo 2002). Logging or deforestation can have a dramatic effect on the drainage patterns of a slope, reducing root moisture uptake, slope reinforcement due to the root systems, and the physical restraints on downslope water flow for example. Such effects were especially noted as factors in the triggering of a translational landslide (not a debris flow) at Loch Shira adjacent to the A83 trunk road near Inverary in December 1994.

Since August 2004 further landslides have affected the Scottish road network on the A82 near Letterfinlay alongside Loch Lochy (January 2005). In addition rock falls have affected the A832 near Kinlochewe (December 2004) and the A82 1.5 miles north of the Corran Ferry junction (January 2005).

Observation and experience indicate that within the recent past, debris flow activity in Scotland has occurred largely, but not exclusively, in the periods July to August and November to January although there is no certainty that such a pattern will continue in the future. However, eastern parts of Scotland do receive their highest levels of rainfall in August. Additionally, climate change models indicate that rainfall levels will increase in the winter but decrease during the summer months and that intense storm events will increase in number. These factors, therefore, may change both the frequency and the annual pattern of debris flow events.

Figure 4. Debris flow at A887 Invermoriston in August 1997. (Courtesy of Northpix.)

Figure 5. Debris flow at A890 Stromeferry in October 2001. (Courtesy and copyright © of Alex Ingram.)

THE RESPONSE TO THE EVENTS

The need to act was recognised by the Scottish Executive to ensure that in the future it has a system in place for assessing the hazards posed by debris flows. In addition, the system must be capable of ranking the hazards in terms of their potential relative effects on road users. Thus the future effects of debris flow events will be able to be managed and mitigated as appropriate and as budgets permit, ensuring that the exposure of road users to the consequences of future debris flows is minimised whilst acknowledging that it is not possible to prevent the occurrence of such events.

As a first, but significant, step towards that overall objective an initial study was set in motion by the then Minister for Transport, Nicol Stephen MSP, to address the following activities:

- Considering the options for undertaking a detailed review of side slopes adjacent to the trunk road network and recommending a course of action.
- Outlining possible mitigation measures and management strategies that might be adopted.
- Undertaking an initial review to identify obvious areas that have the greatest potential for similar events in the future.

A consistent, repeatable and reproducible system was required. This is especially important as a variety of consultants will be involved in the data gathering, analysis and interpretation process. Inevitably each will have a different, but nonetheless valid, approach when operating independently. Such a situation would make any comparison between individual consultant's results and recommendations impossible for the purpose of, for example, allocating funds on a priority basis across the network. It was apparent at the outset that a unified system acceptable to all of the major players in the industry is required.

It was thus recognised at an early stage of the development of the work that the input of a wide range of experts and stakeholders would be required in order for the studies to be completed successfully. In particular, the agreement and input of those most likely to be responsible for using the system was required.

A facilitated Project Workshop was held on 28 September 2004, exactly one month after the events at Glen Ogle, in order to capture the knowledge vested with individual experts who formed a Working Group (see Acknowledgements) led by the authors of this paper. The Project Workshop comprised presentations given by acknowledged experts followed by focussed discussion sessions designed to open out the knowledge base and determine the way forward with the project. Following the Project Workshop the project leaders assigned specific tasks to individuals, including themselves. These tasks were designed to highlight the necessary background material and to develop a way forward for the development of a system described above. The results of the work were incorporated into a technical report (Winter *et al.* 2005a) and a summary report (Winter *et al.* 2005b) designed to inform a wider audience of the Scottish Executive's actions both since the events of August 2004 and planned for the future. These reports were launched at a public seminar held in Edinburgh on 14 June 2005.

This work will lead to a second part of the study which will include the development of a system to allow a detailed review of the network to be undertaken to identify the locations of greatest hazard and for those hazards to be ranked and appropriate mitigation and/or management measures to be selected.

THE WAY FORWARD

A number of areas of perceived high hazard were identified at the Project Workshop. The lengths of road involved are in excess of 160km (Winter *et al.* 2005a). It is thus considered unrealistic to undertake suitably prioritised further evaluations in advance of the GIS-based assessment described below.

The initial stage of the next part of the study will be to develop the methodology for the assessment of hazard and exposure to provide a hazard ranking, together with the selection of an appropriate management approach. The second stage will be to test the methodology before applying it more widely to the trunk road network.

Figure 6 presents a flowchart of the work to be undertaken. The initial stage of this work is itself divided into four elements and can be summarised as follows:

- Development of a debris flow hazard and exposure assessment system to provide a hazard ranking of 'at-risk' areas of the road network.
- Undertaking a computer-based GIS assessment as a first stage in the hazard assessment process.
- Undertaking site specific hazard and exposure assessments of areas identified by the GIS as being of higher hazard.
- The identification and development of appropriate management processes for each category of hazard ranking.

The **GIS-based assessment** will be used as a first stage in the hazard assessment process. This will enable site-specific assessments to be targeted in order to obtain better value from such relatively resource-intensive activities. It will also allow the elimination of large areas of the network having minimal hazard.

It is also particularly important to note that the **site-specific assessment** will not be a 'drive-by' survey; it will require a highly specialised detailed site examination using an overall consistent approach. Prior to undertaking any site surveys it is important that the system for consistently describing and identifying hazards and the associated exposure is established. Some of the factors that will need to be incorporated in such a system, such as slope angle and the broad nature of the geology, will be incorporated into the GIS assessment. Other, more detailed, factors such as the effects of forestation will need to be incorporated into the site-based survey. Once a hazard assessment has been completed it may be combined with an assessment of the exposure of the road user to that hazard to give a hazard ranking. This will allow, in-turn, an appropriate management option to be selected from the range of options to be developed.

There are a number of potential options that could be applied to the management of debris flows. These are addressed in the following paragraphs.

The **'Do-Nothing'** approach is intended to be applied to sites of low hazard ranking for which substantial expenditure is inappropriate. For such sites, whilst it is not possible to eliminate the chance of a debris flow event affecting such areas it is seen as unlikely, largely unforeseeable and/or the exposure is less serious than at other locations where resources may be better expended.

The **'Do-Minimum'** option, with the potential to mitigate the impacts of debris flows to some extent involves simply ensuring that forward plans are in place to ensure that diversion routes are available and may be exploited in an expedient and well organised manner. Diversion route maps and contingency plans are currently held for many areas of the trunk road network.

Whilst it is not possible to eliminate the chance of a debris flow event affecting such areas any occurrence is seen as unlikely and largely unforeseeable. Any residual exposure cannot readily be quantified and is unlikely to justify the commitment of additional resources that may be better expended at other locations.

'Do-Something 1' is the first management option where site-specific action is contemplated. Such action is essentially exposure reduction by managing the access to and/or actions of the road-using public on the network at times either when events occur or precursor rainfall has indicated a high likelihood of debris flows occurring.

'Do-Something 2' involves more major works in order to achieve hazard reduction (as opposed to exposure reduction in the 'Do-Something 1' case). The approaches involved entail physical measures such as the protection of the road, reduction of the opportunity for a debris flow to occur or realignment of the road away from the area of high hazard. Such options need to be considered in the context of the policy governing the Scottish Executive's overall trunk road maintenance and construction programme. In general, these are likely to be of high cost necessitating their restriction to the very few areas of highest hazard ranking.

Exposure and hazard reduction are specifically addressed in the following section.

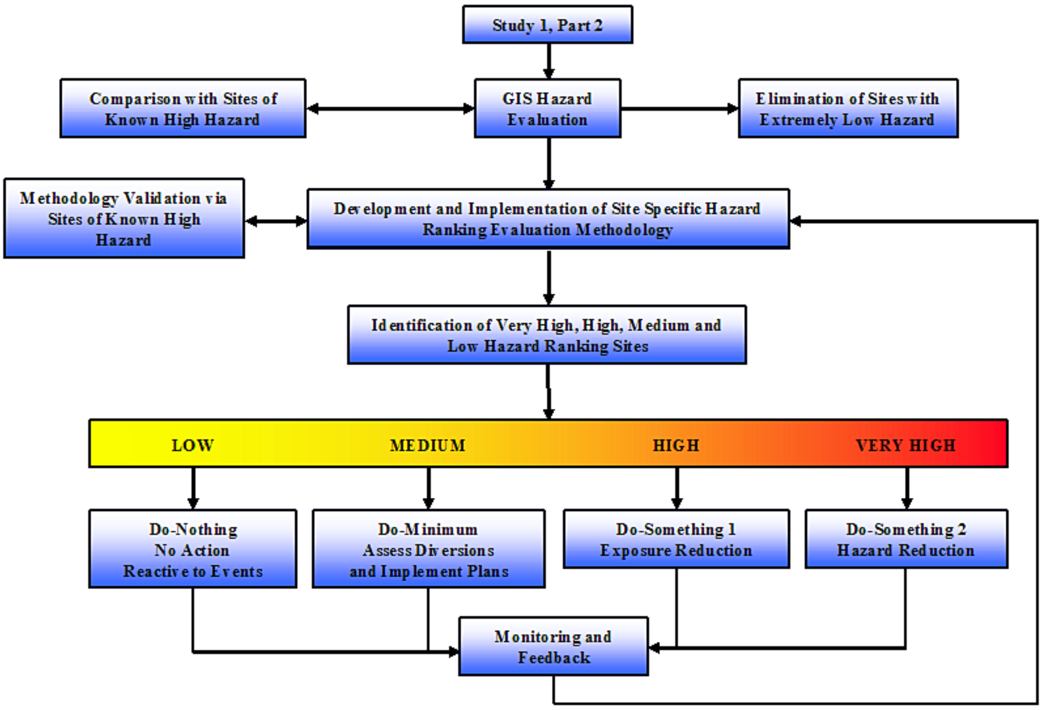

Figure 6. Management and mitigation options.

Clearly, and as illustrated in Figure 6, M**onitoring and Feedback** is fundamental to the success of the system and key to deriving best value from the arrangements proposed. The system developed is an active one and lessons learned from future debris flow events, whether they occur in areas of high or very high hazard ranking or not, will produce valuable data which needs to be taken into account in adjusting the parameters that form the cornerstone of the assessment methodology.

There exists a need to ensure that actions identified by the existing Rock Slope Hazard Index system (as developed in the early 1990s: McMillan & Matheson 1997) are carried out on a priority budget basis. These will include both maintenance works and re-inspection activities. While the rock slope system and the proposed debris flow system have very different structures, great efforts have been made to ensure that the critical exposure evaluation and the output categories are capable of being mutually compatible.

MITIGATION TECHNIQUES

The process described in the previous section culminates in a decision on whether the hazard ranking, in the context of the safe operation of the road network at any location, is acceptable or not. At those locations where the hazard ranking is unacceptable it will be necessary to undertake some form of mitigative action to either reduce the hazard or to reduce the exposure of the road user.

To reduce the hazard to the road user either the magnitude of the hazard and/or the potential exposure or losses that are likely to arise as a result of debris flow must be reduced. To reduce the exposure of road users, the debris flow event is taken as a given and either the number of people exposed to the hazard must be reduced, for example by closure of the road, or they must be warned to exercise caution at appropriate times and places. To reduce the hazard physical intervention is required. In most cases this is likely to be in the form of costly structures and it is anticipated that relatively few locations will justify such expenditure.

Exposure Reduction

The reduction of exposure lends itself to the use of a simple and memorable three-part management tool (Winter *et al*. 2005a), as follows:

- *Detection:* The identification of either the occurrence of an event, by instrumentation/monitoring (e.g. tilt meters or acoustic sensors) or observation (e.g. Closed-Circuit Television, CCTV, monitoring or visual patrols during high likelihood periods), or by the measurement and/or forecast of precursor conditions (e.g. rainfall).
- *Notification:* The dissemination of hazard(s) and exposure(s) information by for example Variable Message Signs (VMS) including NADICS (National Driver Information & Control System) signs, media announcements (radio, TV, traffic guidance systems and the web) and "landslide patrols" in marked vehicles.
- *Action:* The proactive process by which intervention reduces the exposure of the road user to the hazard, by for example road closure, convoying of traffic or traffic diversion.

In the short-term to medium-term the DNA approach to mitigation must be reactive to debris flow events. There may be a case for reacting to extremely heavy rainfall events. However, a caveat to this is the need to consider carefully at what levels the triggers should be set, in so far as the relationship between rainfall and landslides/debris flows in Scotland is by no means fully understood.

In the longer-term, the detection of precursor triggering conditions (i.e. rainfall) may enable both the notification and action phases to be taken prior to the occurrence of major events. However, an extensively enhanced rainfall detection network will be required across Scotland. Even once this is in place it is fully expected that it will take some considerable time and effort to ensure that sufficient data has been obtained and analysed so as to be able to introduce a reliable warning system. Even then it must be expected that atypical events, which are not the subject of warnings, and false alarms may be expected. A programme of public and media education and awareness-raising is likely to be desirable to minimise any potential adverse reaction to such scenarios.

Event Occurrence

Detection: The movement of slope material can be monitored and the resulting information used in a similar way to rainfall data. The data is measured in real time and used as a management tool. Monitoring instruments can be located such as to record movement from potential debris flow or positioned such that notification is received if debris reaches or gets close to a road.

In relation to the former, the seeding area for debris flows can be very large and high on the hillside. This introduces difficulty in pinpointing the optimum location for the installation of the monitoring system and doubt as to whether the debris will reach the road. Installing instrumentation to indicate whether debris has reached a road has precedence: there is a location on the Scottish rail network at Glen Douglas where an instrumented fence has been installed. The purpose of this is to recognise when a fall of ground impinges the line. Similarly the railway through the Pass of Brander above the A85 at Loch Awe has a system whereby any rolling rocks or debris flows trigger signals on the railway that shut the line and stops trains.

It is likely that any instrumentation would be electronic with remote reading of data sent back to a central control point.

Whether such a system is sufficient in isolation is sufficient on its own is questionable, but it is considered that in conjunction with rainfall monitoring and possibly the deployment of operatives the likelihood of road users being affected by debris flow events could be reduced significantly.

The range of possible instrumentation types is presented in Winter *et al*. (2005a) but includes the following: borehole or shallow inclinometers, tilt meters, 'trip wire', 'ball of string', Telemetry, acoustic meters, and remote sensing.

An alternative approach is to use operatives to detect debris flow events by introducing "landslide patrols" during periods of high rainfall. As previously noted it is essential that such operatives are trained in what to look for and that patrols should operate in pairs for safety reasons. Given the wide range of locations at which debris flow activity may be experienced this might prove to be a more practical alternative, the costs of instrumenting and monitoring extensive lengths of slope being potentially prohibitive.

Notification: In the first instance, a debris flow event having occurred, notification must be to the Operating Company and the infrastructure owner. The decision must then be made rapidly to close the road or to keep it open. The nature of debris flows is such that in most cases the road will be blocked and therefore closed to all intents and purposes.

Secondly the public must be warned. In Scotland there is a variety of means of making public announcements when either debris flows have occurred or there is heightened likelihood of their occurrence in an area. This might involve a variety of systems including websites (e.g. NADICS), variable message sign systems and the media (radio and TV) announcements notifying drivers that their potential exposure to the hazards posed by debris flows is real and present. Announcements could also be linked into traffic guidance systems such as TrafficMaster™.

Action: In terms of positive actions that may be taken after a debris flow, a number of options are available. First the road length (or lengths) affected could be closed and appropriate pre-planned diversion routes put in place.

However, it is important to note that closing the road in the area immediately adjacent to the event is not an adequate response. Debris flow propensity is generally believed to affect long lengths of hillside and an evaluation of the vulnerable area must be performed in order to ensure that an appropriate length of road is closed. Closure might be achieved by installing barriers such as the snow barriers present on some of Scotland's roads.

Alternatively trained operatives could be deployed on high hazard ranking sections of road during periods of predicted or actual high rainfall. These operatives could escort people through the high hazard ranking sections of road in convoy (note that while this moves traffic past a potential hazard rapidly if a convoy is hit the losses would be greater than might otherwise be the case).

In all cases re-opening of the road, or its return to normal operation, must only occur after a thorough inspection of the road and the adjacent slopes has been undertaken to ensure that the likelihood of further debris flow events is at an acceptable level. Current practice is to undertake ground-based inspections only when the adverse weather has abated and only to reopen the road once such inspections indicate that the residual hazard and exposure are at an acceptable level.

Precursor (Preparatory or Trigger) Conditions

Detection: Debris flows are initiated, in the main, by heavy rainfall in combination with other conditions. Forecast and real time rainfall data for an area with adverse topographic or other conditions is extremely useful information. If high rainfall is forecast or recorded in such areas then the potential for debris flows will be higher. In certain parts of the world weather forecasting and thereafter rainfall monitoring in real time are two of the controlling factors in landslide management. For example the very successful system run in Hong Kong and that trialled in California both pass information on the heightened likelihood of landslide development to the public as a result of rainfall monitoring.

In the case of Hong Kong, for example, a comprehensive network of automatic rain gauges covers much of the region to record and send data to a central control point for real time analysis. This is combined with short-term forecast data to enable managers to monitor the rainfall as it develops and make informed decisions in an expedient fashion.

If such predictive capability was installed in Scotland then it would be possible to develop systems to reduce the exposure of the road user to the effects of debris flows. However, it must be understood that in Hong Kong more than 20 years of experience have been acquired. This means that a sound knowledge of the relationship between rainfall and landslides is in place relating to the local climate and geology. It is clear that some considerable time would be required to build a similar knowledge base for Scotland, possibly a minimum of five years. A significant investment in instrumentation, data analysis and maintenance would however be required.

Notification: In Hong Kong if the conditions for a 'Landslip Warning' are met then the public are alerted to reduce their exposure to possible danger from landslides. The issue of a Landslip Warning also triggers an emergency system within various Government Departments that mobilizes staff and resources to deal with landslide incidents. A Landslip Warning is issued when it is predicted that numerous (more than about ten) landslides will occur. Nonetheless it is accepted that isolated landslides may occur from time to time when a Landslip Warning is not in force and that Landslip Warnings will occasionally be issued and not be followed by landslides. Landslip Warnings are issued by means of website notices, media announcements and notices prominently displayed in public buildings and areas.

Suitable means of notifying the public are discussed in the preceding section.

Action: If such a system were devised and implemented for Scotland and warnings were received that heavy rain was falling in an area or was approaching an area recognised as being of high or very high hazard ranking then a number of options are available for action. These are broadly similar to those described under event occurrence. However, in the case of road closures it is necessary to be aware of a significant dis-benefit of this approach. Given the relatively rare occurrence of debris flows, at least those that interact with the trunk road network, and the high levels of rainfall that Scotland receives, a number of false alarms could be expected. The public at large could, potentially, become disillusioned at what could be seen as a very conservative approach.

An alternative approach could be to simply notify the public of the heightened likelihood of debris flow development in an area, as described above, and to take no further action until an event occurred.

Hazard Reduction

The challenge with hazard reduction is in identifying locations that are of sufficiently high hazard ranking to warrant spending significant sums of money on engineering works. The costs associated with installing remedial works over long lengths of road are almost certainly both unaffordable and unjustifiable. Moreover the environmental impact of such engineering work should not be underestimated, having a lasting visual impact at the least and potentially more serious impacts. It is considered that such works should be limited to locations where their worth can be proven.

In addition, simple measures such as ensuring that that channels and gullies are kept open can be effective in terms of hazard reduction. This requires that the maintenance regime is fully effective both in routine terms and also in response to periods of high rainfall, flood and slope movement. It is also important that maintenance and construction projects currently in design take the opportunity to limit any hazards by incorporating, where suitable, measures such as higher capacity or better forms of drainage, or debris traps. In particular, critical review of the alignment of culverts and other conduits close to the road should be carried out as part of any planned maintenance or construction activities.

Typically, the reduction in hazard will entail physical engineering works to change the nature of a slope or road to reduce the potential for either initiation and/or the potential for a debris flow to reach the road once initiated. Debris flows are dynamic in nature and are quite often initiated some distance above the road; when they reach the road they are relatively fast moving high-energy flows. The energy of these systems has a significant impact in the nature of the engineering works that can be used to reduce the hazard to the road and its user. Hence, there are three broad approaches to selection of hazard reduction works:

- Accept that debris flows will occur and protect the road.
- Carry out engineering works to reduce to opportunity for a debris flow to occur.
- Realign the road.

In relation to the first option there are not many examples of such engineering works in Scotland or the rest of the UK, but in some upland areas of mainland Europe such engineering is relatively commonplace. The energy of the debris flow is such that a rigid barrier constructed to protect the road would have to be designed for very high loads. In essence a debris flow has significant momentum and to bring it to a sudden stop, as is the case with a rigid barrier, requires the dissipation of a lot of energy, instantaneously imparting very high loads.

Road Protection

Debris Basin: These essentially comprise a large decant structure with a downstream barrier designed and constructed as an earthfill dam capable of retaining water to full height in the event that the drainage outlet(s) become completely blocked (Figure 7). In larger examples a concrete spillway is often incorporated into the downstream face of the barrier to protect the earthfill from erosion in the event of overtopping and irregular surface features may be used to slow the passage of the debris (Figure 8). The channel below the structure can been lined with concrete and boulders in order to control (slow) both flood flows and debris flows in the event of over-topping (Couture & VanDine 2004).

Figure 7. Debris basin showing the downstream barrier and drainage outlet, Mackay Creek, N Vancouver, BC, Canada.

Figure 8. Concrete spillway on the downstream face of a debris basin barrier, Charles Creek, Sea-to-Sky Highway, BC, Canada. The drainage outlet may be seen in the centre of the spillway.

Lined Debris Channels: Where storage space upstream of the road is limited an alternative approach may be taken and steps taken to move the material safely beneath and on to a safe repository area, usually a large body of water such as the sea or a loch. Couture & VanDine (2004) illustrate the use of a steel-fibre reinforced shotcrete lining in smooth well-aligned stream channels in order to smoothly and swiftly move material below the road (Figure 9). It is also recognised that relatively low cost, simple improvements to channel flow down to and beneath the road may have a beneficial effect; this may be achieved by widening culverts. for example.

Debris Flow Shelters: Stone shelters or 'avalanche shelters' are engineered structures that form canopies over a section of road prone to rock fall or debris flows. These structures are usually formed from reinforced concrete. There is an example of such a structure on the A890 north-east of Stromeferry in the north-west highlands. This structure straddles both the road and railway at that location. Energy is dissipated by placing a depth of granular material on the roof on which the debris flow lands.

Debris Flow Overshoots: In situations where the energy is anticipated to be very high, modifications can be made to debris flow shelters to allow the debris flows to pass over the top of the structure. This is done by shaping the top of roof of the shelter such that the falling material passes over the structure without dissipating much energy. This shaping or profiling involves constructing a 'ski-jump' type reinforced concrete structure. Material falling simply slides over the roof and continues down the hillside.

Barrier Fences: Fences can be constructed to act as effective barriers to halt debris flows. Such fences are designed to be flexible so that the energy of the debris flow is dissipated over a short period of time thus reducing the forces that the structure has to cater for. These systems have been shown to work well. Such a fence has been installed on the Inverness to Kyle of Lochalsh railway in Scotland. Such fences do require maintenance after the impact of a debris flow. A related approach has been taken to the arrest of rockfalls using highly flexible fences with fixed end-posts only.

Flexible fixed position fence structures are commonplace in upland areas of mainland Europe and while the UK does not have engineering design standards for such structures, experience is available and formalised procedures do exist, particularly in Switzerland.

Figure 9. Stream/debris channel, Alberta Creek, Sea-to-Sky Highway, BC, Canada

Debris Flow Prevention

The applicable engineering solutions to the prevention of flow will depend strongly upon the individual circumstances. Debris flows can have a relatively large source area and be initiated very high up on the hillside above the road. In most circumstances the potential for carrying out conventional remedial works to restrain the material before it starts to move is considered to be very limited. There may be particular conditions where a combination of techniques such as gravity retaining structures, anchoring or soil nailing may be applicable. However, in general terms the cases where these are applicable and economic are likely to be limited.

The link between debris flows and intense rainfall has been established previously in this document. As a result water management can reduce the potential for debris flow initiation.

In the circumstances of the debris flows that occurred in the summer of 2004 it is considered that on hill drainage improvement would have had little impact due to the scale of the events. In other locations positive action to improve drainage may well have a beneficial effect. This would include improving channel flow and forming drainage around the crest of certain slopes to take water away in a controlled manner.

Road Realignment

Road realignment can be used as part of the Scottish Executive's structural management activities in order to improve the road in terms of both alignment and junction layout, in particular to reduce accidents and also to ensure compliance with current design standards. In cases where the hazard ranking from debris flows is high and other factors indicate that some degree of reconstruction is required, road realignment may be a viable option. Similar expedients have historically been used on the Scottish rail network, for instance at Stromeferry, Penmanshiel and Dolphinston, where hazards have been sufficiently significant to justify the high cost of such realignments.

SUMMARY AND CONCLUSIONS

The Scottish landslide events of August 2004 have been briefly described. These were in the form of debris flows. While such events are relatively common, such a significant degree of interaction with the transport infrastructure is unusual.

The Scottish Executive has initiated and led a rapid, proportionate and structured response to these events. An inclusive approach has been adopted to the involvement of a wide range of acknowledged experts each of whom has a vested interest in producing an appropriate system for the future assessment, ranking, management and mitigation of debris flow hazards on the Scottish road network. The response to these events has been described in some detail.

The way forward in terms of the development of the system has been described. This will provide a systematic means of ranking hazards and thus allowing the allocation of funds on a priority basis across the network. Four levels of hazard ranking are described and two of these are intended to attract specific site-specific actions.

At sites of high hazard ranking, exposure reduction is anticipated; this will be based upon the logical sequence of Detection-Notification-Action (DNA). In the short-term the DNA sequence will be applied in a manner so as to react to debris flow events. In the longer term an enhanced network of rainfall gauges that will allow the detection of precursor conditions such that notification can be made and action taken in advance of debris flows occurring is planned.

At sites of very high hazard ranking, hazard reduction is anticipated; such actions will, in the main, involve the expenditure of significant sums of money on engineering works. The costs associated with installing remedial works over long lengths of road are almost certainly both unaffordable and unjustifiable. Moreover the environmental impact of such engineering work should not be underestimated, having a lasting visual impact at the least and potentially more serious impacts. Such works should be limited to locations where their worth can be proven.

Clearly many of the mitigation techniques and activities described will require a heightened level of awareness of the issues surrounding landslides in general and debris flows in particular from engineers, the public and the media. As such partnership, education and knowledge dissemination will be a key part of the ongoing work.

It seems clear that the system as described will provide significant benefits in terms of the reduction of the impacts of future debris flow events that may impact on the Scottish road network.

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